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Middens, currents and shorelines: Complex depositional processes of waterlogged prehistoric lakeside settlements based on the example of Zurich-Parkhaus Opéra (Switzerland)

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ABSTRACT

Circumalpine lakeside settlements have been declared Unesco world heritage in 2011. Their importance is mainly due to waterlogged preservation of organic material and hence the outstanding potential of these sites for performing detailed archaeological studies of prehistoric societies. However, the details of the taphonomic processes (depositional environment, development of anoxia, lateral or vertical displacement of objects, etc.) have rarely been studied. Consequently, interpretations based on find distributions or comparisons of find densities remain difficult. Zurich-Parkhaus Opéra is a large-scale excavation of waterlogged Neolithic settlement deposits. Eight settlement phases of the late fourth and early third millennium BC were documented and dated using dendrochronology as well as six settlement layers, two of which showed excellent organic preservation. Based on a large number of sediment samples we conducted a multidisciplinary study in taphonomic processes influencing these layers. Our results indicate that a multi-indicator approach can provide detailed information on formation processes of waterlogged cultural layers. We found that 1) aquatic invertebrate remains and geotechnical calculations gave evidence for continuous shallow water conditions and eutrophic/anoxic deposition environment during occupation of the site. 2) Position and distribution of finds and loam patches indicate that disposal of household waste was focused on middens, which were still intact. 3) High variability in sediment contents (both spatially and in terms of state of preservation) is due to different factors such as oxygen depletion, deposition rate, erosion and enrichment of different materials, while all factors can affect each other resulting in highly complex formation processes.

1. Introduction

Prehistoric lakeside or wetland settlements with waterlogged deposits are common around the Alps. They have been the focus of archaeological research since the 19th century and form part of the Swiss national identity (Kaeser, 2004). However, similar sites exist in a much wider regional context. In Europe, wetland sites have as well been found e.g. on the Balkans (e.g. Chrysostomou et al., 2015; Todoroska, 2016; Naumov, 2016), the Baltics (e.g. Menotti et al., 2005) or Poland (e.g. Pydyn and Gackowski, 2011; Czebreszuk et al., 2010), but they also occur in other non-European regions (Menotti and O'Sullivan, 2013).

Large-scale excavations of coherent areas in such sites are rare, due to their high costs and complexity. Particularly, systematic interdisciplinary studies of the finds and sampled material are needed, since only under these conditions can such organically preserved settlement deposits be fully exploited for developing palaeoeconomic and -ecological studies e.g. concerning land use and the development of cultural landscapes (Jacomet et al., 2016) or for producing reconstructions of past social history (e.g. Röder et al., 2013; Schibler and Jacomet, 2010). In this paper, we discuss recently excavated finds and analysed samples from the large scale excavation of Neolithic settlements at Zurich Parkhaus Opéra (Switzerland). Based on the detailed findings from this site

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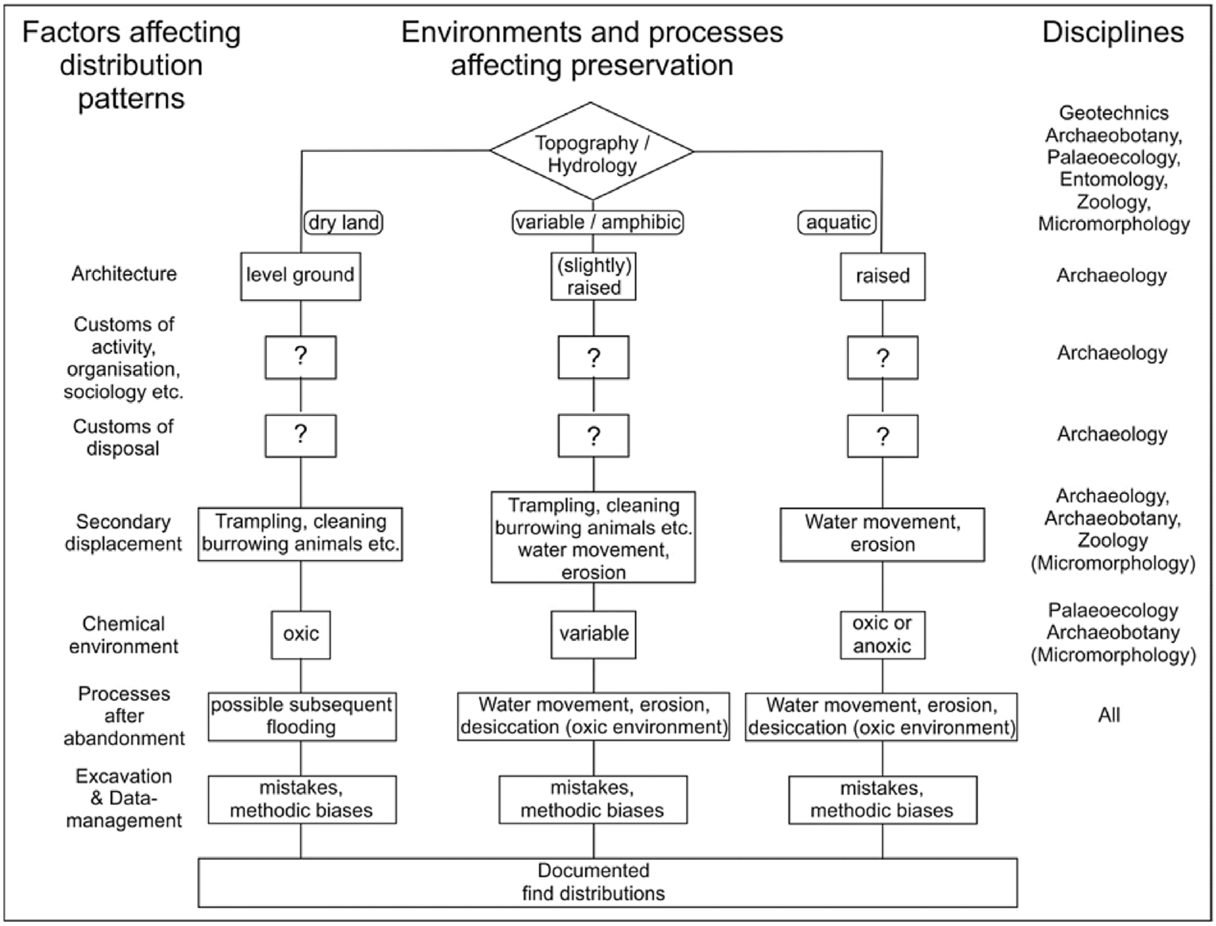

Fig. 1. Environments and processes determining and influencing find distributions in lakeside settlements and the disciplines that can contribute to their reconstruction.

we first try to identify the most important taphonomic processes that influenced layer genesis of these deposits and more generally affect preservation state and find distributions in prehistoric lakeside settlements.

The interpretation of rich datasets such as those obtained at our study site requires a thorough understanding of the particularly complex site formation processes in lakeshore environments.

Formation processes have been studied for decades (Schiffer, 1987), but mostly for sites on mineral soils. However, in wetland archaeology there have been a number of studies and sites for which these questions have not been answered in detail (e.g. Eberli, 2002, 87), where contradictions between disciplines led to discussion (e.g. Dieckmann et al., 2006, 198) or where results from some disciplines were not fully integrated into archaeological theories (e.g. Joos et al., 1980). The difficulties that cultural layers in lakeside settlements pose for research and interpretation gave rise to intense debate (see Dieckmann et al., 2006, 207–219; Bleicher, 2015) and were part of the reasons, why in some cases analysis and publication of the layers was delayed for decades (e.g. Ebersbach, 2015, 11).

In the past, taphonomic studies of waterlogged deposits at former lake shore settlements mostly focused on plant and animal remains or micromorphology of sediment structures (Jacomet, 1985; Brombacher and Hadorn, 2004; Deschler-Erb and Marti-Grädel, 2004; Ismail-Meyer, 2014; Steiner et al., 2018). Some of these studies aimed at high (micro-) stratigraphical resolution although only for a very limited area of the examined archaeological sites. In contrast, at Zurich-Parkhaus Opéra we focused on a combined examination of high-resolution stratigraphic analyses at several profile monoliths and extensive sediment scatter samples (according to Lennstrom and Hastorf, 1992) of large volume, which we call in the following text surface samples (for details see Steiner et al. 2017). These were systematically extracted from archaeological deposits across a large section of the excavated area. The analyses were supported by geotechnical calculations and detailed spatial analyses of find distributions.

1.1. General considerations on taphonomy in wetland sites and aims of this paper

Reconstruction of cultural customs are the original aim of archaeology but this relies on the clarification of all other processes. Numerous factors determine both distribution patterns of objects in settlements and whether these are preserved or not. Regarding lakeshore settlements, these factors have been conceptualised as a series of processes at four levels or stages during layer formation (Bleicher, 2013). For the present study this concept has been expanded by including the topographical and chemical environment. Factors affecting distribution patterns are different in various environments (Fig. 1).

The depositional environment is crucial for wetland taphonomy, as it determines whether organic material is preserved. It is characterized by local physical and chemical factors, the most important of which are

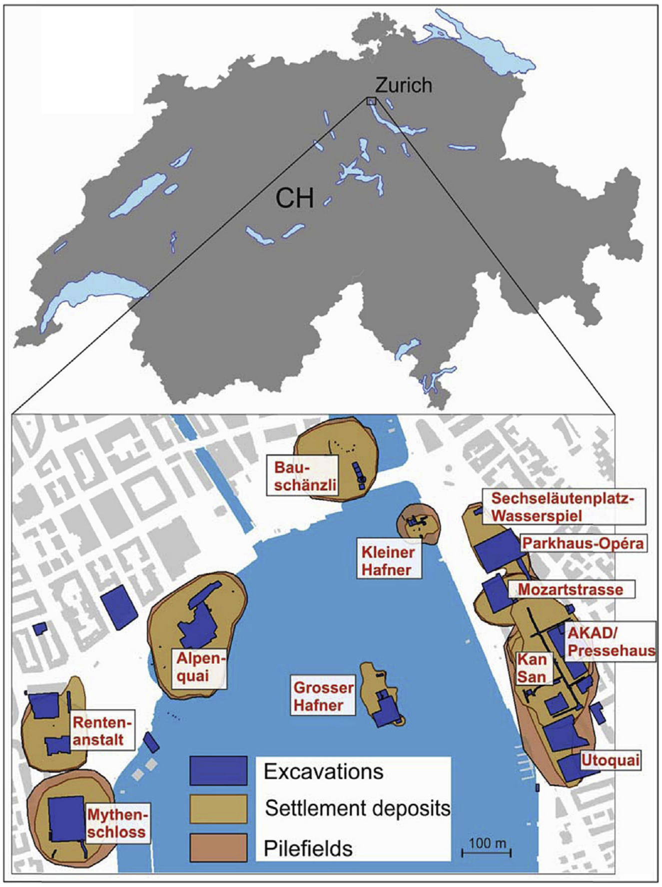

Fig. 2. Map of prehistoric lakeside settlements in Zurich.

water saturation of the substrate and the nutrient content of the overlying water (in aquatic environments), as these define whether anoxia develops and organic materials preserve. Anoxic or hypoxic conditions occur when oxygen demand for degradation of aquatic production and other easily degradable material from allochthonous sources (such as faeces and waste) exceeds oxygen supply to the water or the sediment. Organic preservation is therefore the result of a surpassed threshold in the relation between the rates of organic deposition, loss of organic remains through erosion, organic degradation and oxygen supply (Bleicher and Schubert, 2015). Strictly speaking, trophic state (reflecting nutrient availability, Smith et al., 1999) and saprobity (i.e. intensity of degradation and biological oxygen demand, Tagliapietra et al., 2012) need to be distinguished. Even water bodies with low nutrient levels may locally be characterized by high levels of saprobic processes, where organic input (e.g. from terrestrial sources) and degradation are intense. High rates of decomposition cause high rates of nutrient release, promoting higher nutrient levels and trophic states, which in turn may cause more plant growth (especially of plants that prefer high nutrient levels) and this can reinforce organic deposition and decompositional processes. At lakeside settlements, trophic state of the water and sabrobity can be expected to have been closely linked. For simplicity we will use the term eutrophication when referring to both of these co-occurring phenomena, since they both can lead to oxygen depletion and lastly to organic preservation. In the absence of human impact, open water and the sediment-water interface were most probably oxygen-rich environments in most near shore areas of large hardwater lakes such as Lake Zurich, except perhaps in dense aquatic macrophyte stands (e.g. reed belts). These environments were characterized by comparably low nutrient concentrations before anthropogenic eutrophication (Killops and Killops, 1993, 75; Lotter, 1998). Under these conditions, most of the few organic remains (e.g. water plants, autumn litter etc.) degrade rapidly. This results in lake marl usually containing only low abundances of organic macroremains except for *Characeae*-oogonia. Local eutrophication events associated with lakeside settlements need not affect the whole lake, but can affect the microstructure of fauna, flora and morphology of near-shore environments locally. Plants such as *Phragmites* that grow well under higher nutrient concentrations can form belts along the waterside (Ostendorp, 1993, 178–179). These in turn can act as traps for different materials including archaeological finds.

Post-settlement processes also affect deposits. Even if anoxia developed during occupation of the site, organic preservation is dependent on subsequent oxygen availability, which in turn depends on the deposition rate of micrite. Lake marl has small interstitial spaces reducing oxygen diffusion and leading to low oxygen levels in depths of only few millimetres (Caple, 1994, 67; Maerki et al., 2009, 431). Insufficient micrite deposition, changes in water level or later erosion events can expose organic deposits to oxygen and cause their degradation.

Main aim of this paper is to understand the depositional environment at the site. For this, we analysed indicators for the degree of preservation as well as for oxygen availability and eutrophication at the time of deposition in several cultural layers. We compared these with the microstructure of the sediment matrix and geotechnical model results. To identify factors affecting find distributions we analysed various indicators for sediment and find mobility and analysed find distributions as well as find densities in relation to layer thickness for materials of different specific weight.

2. The site Zurich-Parkhaus Opéra

In 2010, the construction of an underground parking facility led to a large-scale rescue excavation of a Neolithic waterlogged settlement site in Zurich, Switzerland (Fig. 2). Within 9 months, a team of up to 60 workers excavated roughly 3000 m^2 under difficult technical conditions and a tight schedule recovering six settlement layers with different degrees of organic preservation. Dendrochronological and radiocarbon dating revealed that the site contains eight (and not six as initially assumed) late and end Neolithic, settlement phases between 3234 and 2727 BCE (Fig. 3). Two phases are contained in one common layer and the lowest cultural layer contains sediments from several events that could not be separated based on stratigraphical analysis. The oldest and youngest deposits contained hardly any organically preserved remains, while two layers (Layers 13 and 14) consisted of waterlogged organic material. The cultural layers consist of organic debris, as well as loam deposits and other mineral components including ash, sand and lake marl (in the following we will use the term micrite). The definitions of the different sediment types based on micromorphological analyses are described in the Electronic Supporting Material (ESM).

The reconstruction of buildings based on dendroarchaeological analyses of wooden piles revealed that both density of buildings and duration of occupation were roughly uniform across the site within the individual (sub-)phases (Bleicher and Burger, 2015; Bleicher and Harb, in press).

In total, more than 20,000 finds were recovered and over 2000 surface sediment samples and samples from monoliths (sediment blocks recovered from profiles) were taken systematically for bioarchaeological, sedimentological, micromorphological and palaeoecological studies. More than 20,000 piles and horizontal woods were documented

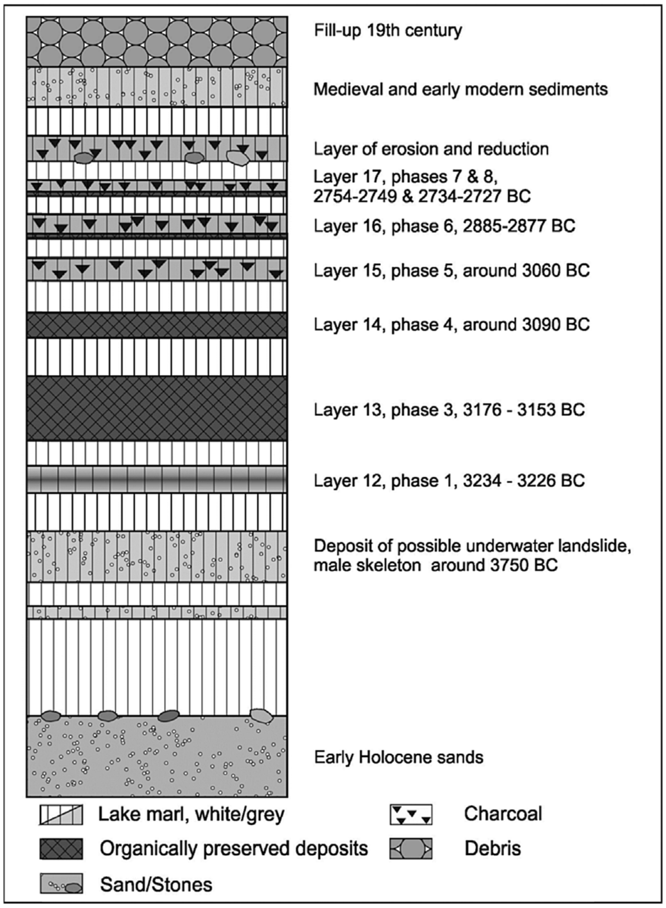

Fig. 3. Idealised stratigraphy of archaeological deposits at Zurich Parkhaus Opéra with associated dendrochronological dates (Bleicher and Burger, 2015).

and analysed. Starting in 2012 an interdisciplinary study of these samples was undertaken, involving a wide range of disciplines (Bleicher and Harb, 2015, 2017, 2018; Harb and Bleicher, 2016).

3. Material and methods

In the following we will discuss methods and results first for topography, hydrology and the chemical environment and then for inferring material loss and displacement. The methods applied during excavation and documentation are given in detail in the ESM.

3.1. Methods for the analysis of topography, hydrology and chemical environment

In order to clarify the topographic and hydrologic settings, we followed a multiproxy approach. First, we reconstructed the former topography using geotechnical calculations. This was done by reconstructing the history of sediment deposition using both the excavation documentation as well as, for younger deposits, historical written sources. This information was entered into standard geotechnical finite-elements software for modelling sediment consolidation, along with data from compression experiments conducted on local sediment. In an iterative process many different initial topographies were tried out and the results of the modelled consolidation after 5000 years were compared to the actual situation in 2010 (see Schneider et al., 2015 for method details). In this way we produced an estimation for the original topography of the archaeological site in 3200 BCE (Fig. 4).

In a second step, we evaluated the contents of the systematically obtained surface sediment samples from waterlogged Layers 13 and 14 (Fig. 2). To constrain the hydrologic setting we assessed the densities of remains from aquatic organisms (see ESM). The organic fraction was examined for plant and insect remains, which were then identified (Antolín et al., 2017a; Schäfer, 2017). During the identification of the botanical macroremains we also documented indications for preservation state, chemical corrosion and mechanical erosion, for example the surface structures of hazelnut shells or the presence of leaf fragments with intact tissue (Fig. 5; Antolín et al., 2017b). The inorganic fraction was examined for remains of molluscs, fish and bones of small animals (Hüster Plogmann and Häberle, 2017). The laboratory procedures of the individual disciplines are provided in the ESM.

Next to surface samples we sampled profile monoliths from various places within the excavated area (Fig. 4). We selected a number of these for high-resolution analyses of chironomid and cladoceran remains as well as pollen (Heiri et al., 2017; Gobet et al., 2017). Chironomid concentrations and assemblage composition at the subfamily/tribe level reported here were quantified when examining sieved sediment samples, sorting chironomid remains and mounting these on microscope slides. Similarly, cladoceran concentrations and assemblage composition changes at species level were quantified following chemical treatment and sieving of sediment sub-samples and mounting cladoceran remains on microscopic slides. Identifications under the compound microscope are presented in detail in Heiri et al. (2017). The remainder of the monoliths was used for analysing sediment micromorphology (Pümpin et al., 2015).

Additionally, profile photographs were systematically examined for differences between the structure of cultural deposits on the lakeward side versus the landward side of the former settlements. Special attention was given to the lower transition zone from micrite to Layer 13 (Figs. 6 and 8). This transition occurred in different forms (sharp or diffuse boundaries). For some of these transitions micromorphological analyses are also available (for the methods see ESM).

Finally, loam patches and horizontal timber were mapped (Bleicher and Ruckstuhl, 2015) to look for evidence of constructions preserved *in situ*. Such constructions are of relevance for the present study since the possible architecture is determined by hydrology and can therefore be seen as an indicator for hydrology as well.

3.2. Methods for assessing secondary displacement and material loss

Mapping of finds is the foremost approach used for testing whether objects show uniform distributions or lie in clusters or lines. We hypothesized that removal of material by water currents would be in some relation to the objects' weight and/or specific density. Heavy ceramic pots or stone adzes are more stationary than e.g. textiles, cereal chaff or more generally the fine-grained plant detritus that forms the organic deposits' matrix. We therefore calculated find densities for material with different weights in selected stratigraphical positions, in order to find traces of enrichment or depletion. Due to different degrees of preservation both in quality and space, such calculations were only possible for Layer 13 in Parkhaus Opéra. In addition, detailed individual observations can be very informative, such as lateral movement of material into cavities.

4. Results

For both layers of organically preserved deposits (Layers 13 and 14) the results were characterized by similar depositional patterns (see

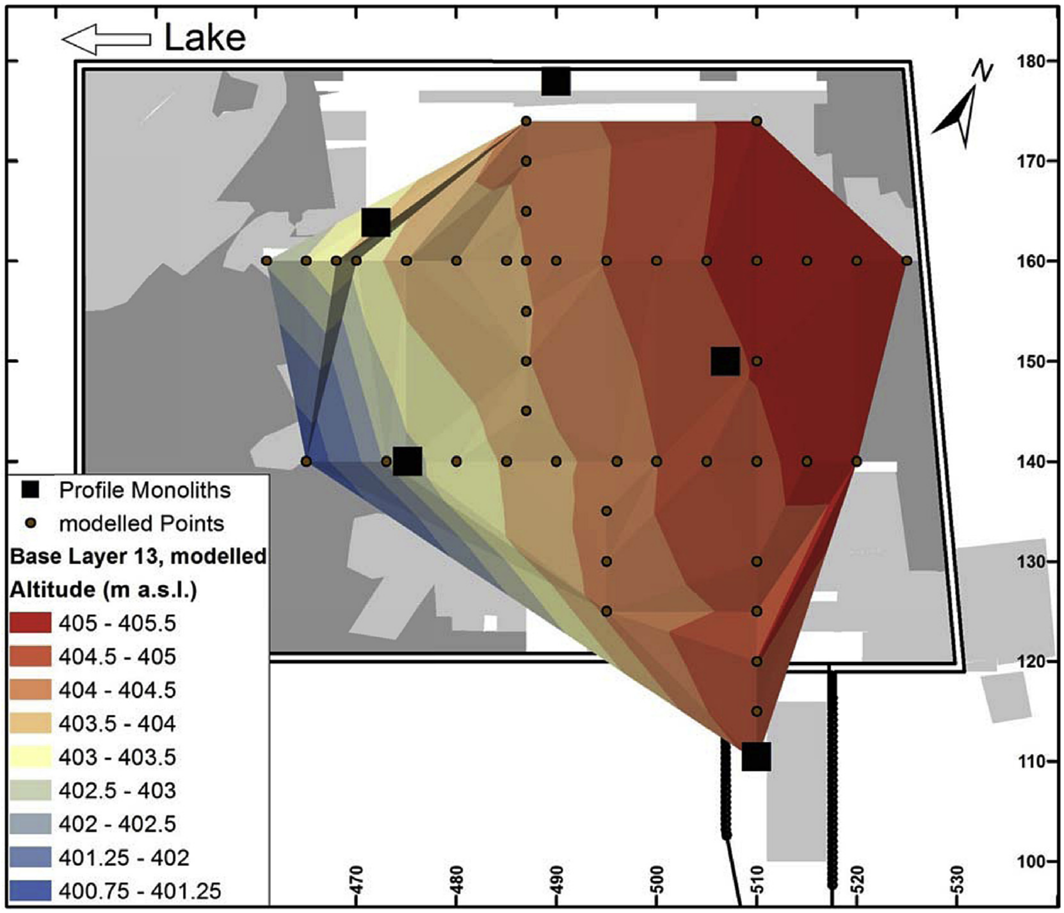

Fig. 4. Reconstructed topography of the excavated area in 3200 BCE (after Schneider et al., 2015).

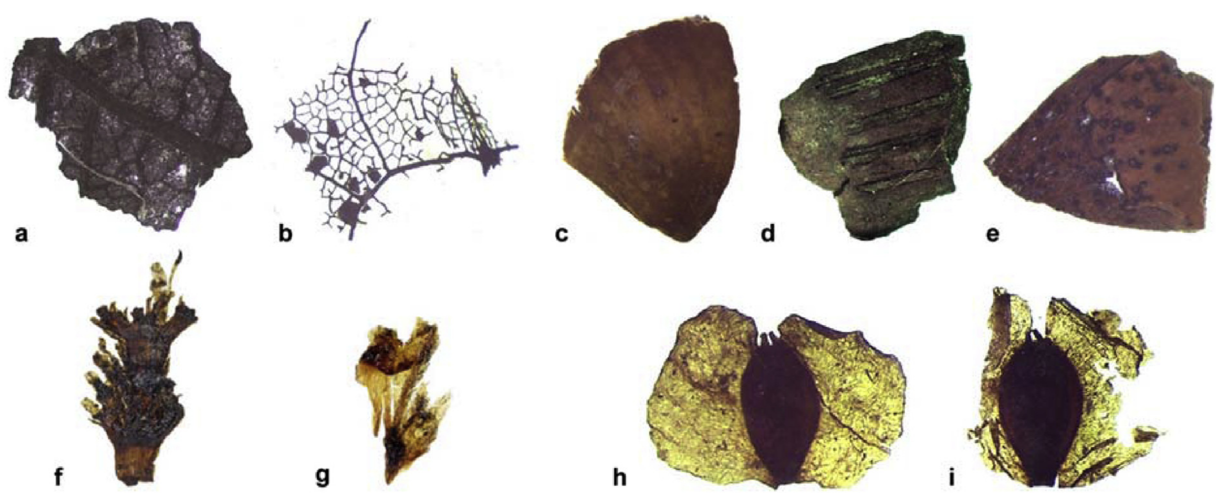

Fig. 5. Indicators of preservation state, mechanical erosion and chemical corrosion in botanical remains (Antolín et al., 2017a): a: leaf blade, well preserved; b: leaf blade, only veins preserved; c: hazelnut shell, well preserved; d: hazelnut shell, eroded surface; e: hazelnut shell with fungi; f: rachis fragment of barley (*Hordeum vulgare*), well preserved; g: rachis fragment of barley, poorly preserved; h: winged seed of birch (*Betula sp.)*, well preserved; i: seed of birch, poorly preserved.

references in sections 2.1 and 2.2.), so they are discussed together in this paper.

Cultural layers consisted mainly of organic detritus that could not be differentiated into separate stratigraphical bodies. The detritus was interspersed with frequent loam patches (mostly multi-layered) of few square meters in size (Figs. 7 and 8). Nearly all loam depositions were characterized by randomly positioned fragments of burnt surfaces. None of the loam deposits contained wooden substructures. Horizontal

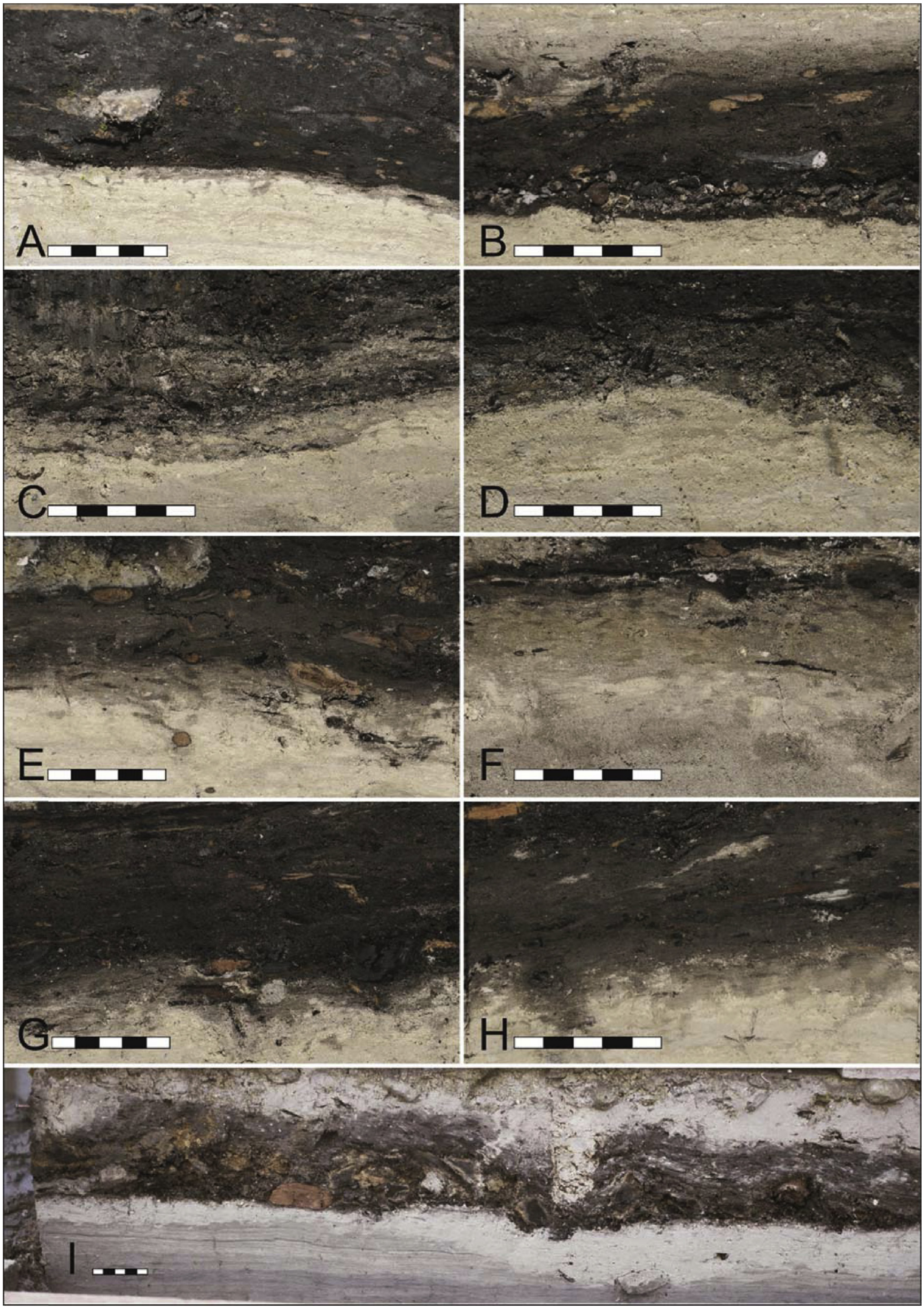

Fig. 6. Types of transition zones between micrite and organic anthropogenic deposits (A-H all Parkhaus Opéra, I: Hornstaad-Hörnle IA (Germany)). A and B: sharp boundary with and without a thin grey base layer that probably reflects bioturbation. C: possible mechanic intrusion. D: Sharp boundary with higher amount of sand/ fine gravel at the base. E–H: Different types of diffuse or undulated boundaries with a base layer of a few centimeters thickness, consisting of mixed materials. I: sharp disruption of banded structure in micrite at the base of a deposit.

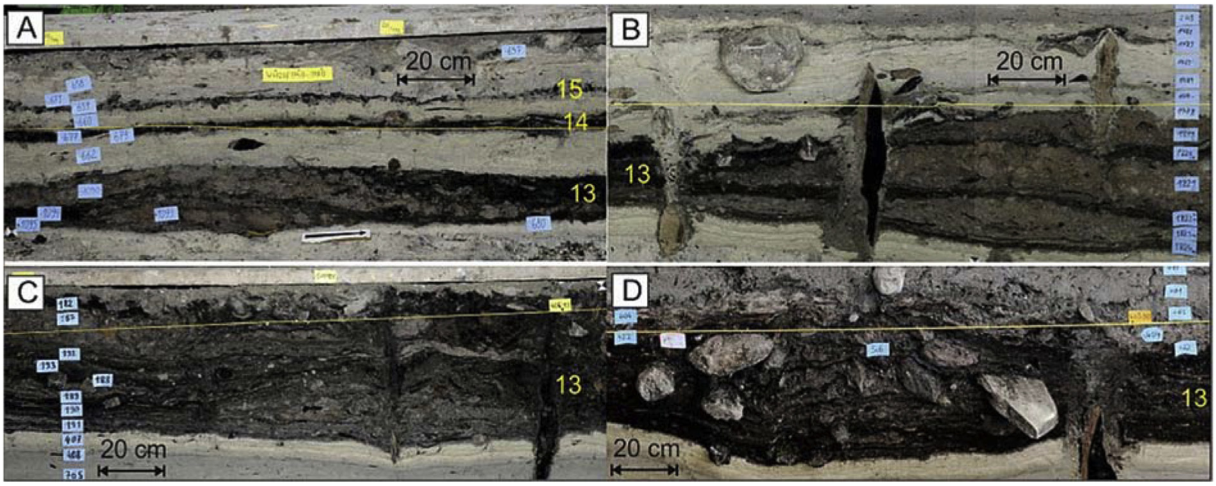

Fig. 7. Sediment profiles exemplifying loam structures (A and B) and mineral concentrations without clay (C and D) in organic anthropogenic deposits. Bright deposits consist of micrite of limnic origin.

timbers lay in random order. Comparison of the distribution of the loam deposits with outlines of buildings identified during dendroarchaeological pile field analysis revealed that loam deposits were consistently located close to the centres of rectangular buildings (Bleicher and Burger, 2015; Bleicher/Harb, in press). A second phenomenon that was regularly observed within the organic deposits were concentrations of different mineral contents like stones, bones, silex, ash and unidentified silt material (Fig. 7). These were often interspersed with the loams and very rich in finds (Fig. 8).

The analysis of the loam deposits in Layers 15 and 16 showed that

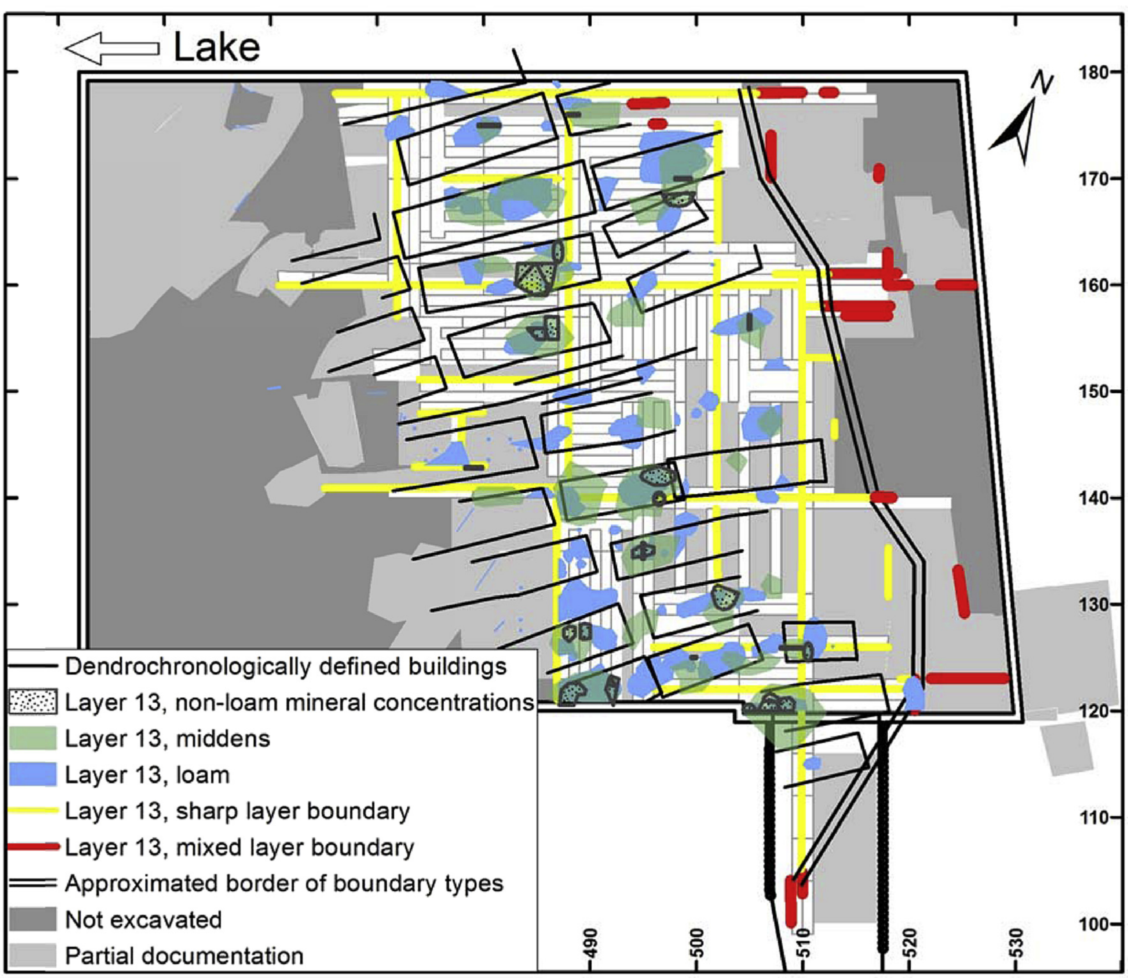

Fig. 8. Loams, mineral concentrations and the border between sharp and diffuse boundaries between basal micrite and organic detritus in Layer 13 in relation to dendroarchaeologically identified buildings. Transition zones between micrite and cultural layers of types A-D (see Fig. 6) are mapped in yellow. Types E-H are mapped in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

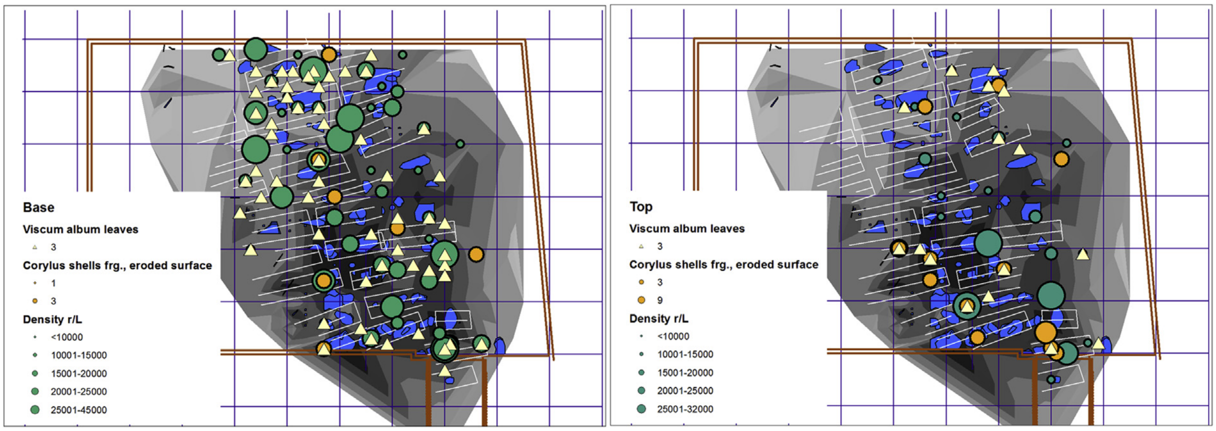

Fig. 9. Example of botanical data providing evidence for preservation quality. The panels show distributions at the base and the top of the stratigraphy. Find densities of *Viscum album* leaves are indicators for very good preservation, while eroded surfaces on fragments of hazelnut shells are indicative of mechanical strain.

their internal structure was the same as in Layers 13 and 14. In Layer 17, no loams were deposited or preserved.

4.1. Results on topography, the hydrological setting and the chemical environment

The geotechnical reconstruction of the topography for 3200 BCE suggested that the excavated area had a slope to the lake of up to 10%, resulting in differences in reconstructed elevation of up to 5 m between the most lakeward and the most landward buildings (Fig. 4). Part of the settlement was originally well below 402.5 m a.s.l. (Schneider et al., 2015), which is probably the lowest possible lake level for Lake Zurich because of a hard rock barrier at the outflow (Schindler, 1981).

For most of the excavated area, we found sharp boundaries between natural micrite, containing undisturbed lamina-like bands, and the anthropogenic organic detritus with little or no signs of mechanical disruption or mixing (Figs. 5 and 8). It is only on the most landward side of the area that we found diffuse, undulated boundaries between basal micrite and cultural layers.

All involved disciplines found the preservation of organic remains to be generally good to excellent. Delicate objects such as cereal chaff remains and even green leaves were regularly present (see some examples on Fig. 5), which is indicative of very quick burial and oxygen depletion. However, both archaeobotanists and micromorphologists also noted numerous evidences for corrosion and erosion in the same samples. The intermixture of good and poor preservation states occurred over the entire area and in all stratigraphic positions within cultural layers.

Detailed botanical analyses demonstrated for Layer 13 that find densities and preservation states were highest in the lower part of the cultural layer, with concentrations regularly reaching 10,000 (sometimes even 20,000) remains per litre. Traces of mechanical erosion such as e.g. hazelnut shells with eroded surfaces were somewhat more common on the lakeward side of the excavation area (Fig. 9). The intermediate layers between the loam deposits showed heterogeneous preservation states with higher frequencies of poor preservation, especially due to mechanical destruction. At the top of the stratigraphic sequences find densities were similar to those in the intermediate layers. Examples of erosion were frequent and high densities of delicate objects were rare, indicating more intense chemical corrosion. In all stratigraphic positions within the cultural layers including the intermediate layers, where post-depositional contamination with over- or underlying micrite can be excluded, remains of water plants were regularly found, even if not in high densities (Antolín et al., 2017a, 59f.; Fig. 7). Especially in the upper parts of the anthropogenic layer, as well as on top of it, water plants such as *Najas* sp. dominate. These are indicative of eutrophic conditions and contrast with the typical Characeae (algae) that characterise micrite layers between anthropogenic deposits (Jacomet, 1985; Steiner et al., 2018).

Insect remains from the surface samples of the cultural layers originated from species that inhabit a wide variety of biotopes. Water insects and especially *Trichoptera* species that live in eutrophic water bodies with many macrophytes were ubiquitous and found in high abundances (ESM, Table 1). Aquatic invertebrates were most frequent in lower parts of the cultural layer and became increasingly rare towards its top (Schäfer, 2017).

The data on molluscs revealed a similar picture: of more than 6700 analysed remains, all but 21 remains stem from obligate aquatic species, many of which prefer eutrophic water rich in macrophytes. The most frequent type of remains was the operculum of the gastropod *Bithynia tentaculata* (Hüster Plogmann and Häberle, 2017, Fig. 136). The 21 terrestrial remains were from snails.

Aquatic invertebrate analysis of samples obtained from the monoliths revealed that changes in chironomid communities accompanied each transition from lake marl to cultural detritus layer and back, apparent both at the subfamily/tribe level (Fig. 10) but also at higher

Table 1
Comparison of the loss of finds in comparison to layer thickness (Lt) of Layer 13.

	Absolute		Percent		Trend
	Lt = 10 cm	Lt = 30 cm	Lt = 10 cm	Lt = 30 cm	Loss/cm Lt in %
Ceramics (g)	100	195	51%	100	2.45
Stone tools (n)	115	210	55%	100	2.25
Silices (n)	99	190	52%	100	2.4
Bone/Antler (n)	450	1650	27%	100	3.65
Bone/Antler (g)	6.5	19	34%	100	3.3
Layer thickness (Lt)	10	30	33%	100	3.3

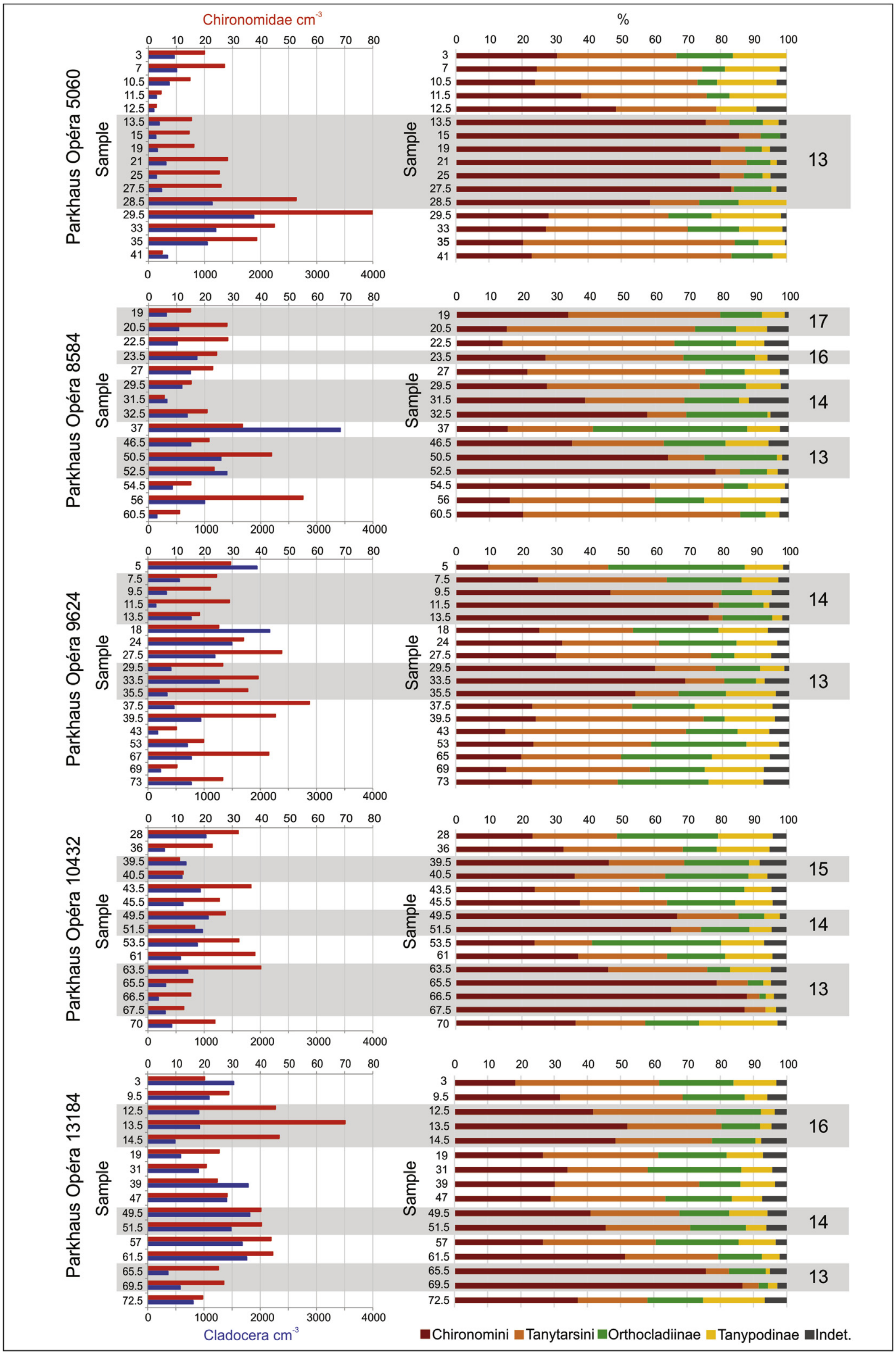

Fig. 10. Concentrations of chironomid and cladocera remains (left) as well as the percentage abundance of major chironomid groups (subfamilies and tribes, right) in the studied sediment columns (Heiri et al., 2017). Sample labels represent relative sediment depth (in cm) on the sediment columns. Grey bands indicate cultural layers.

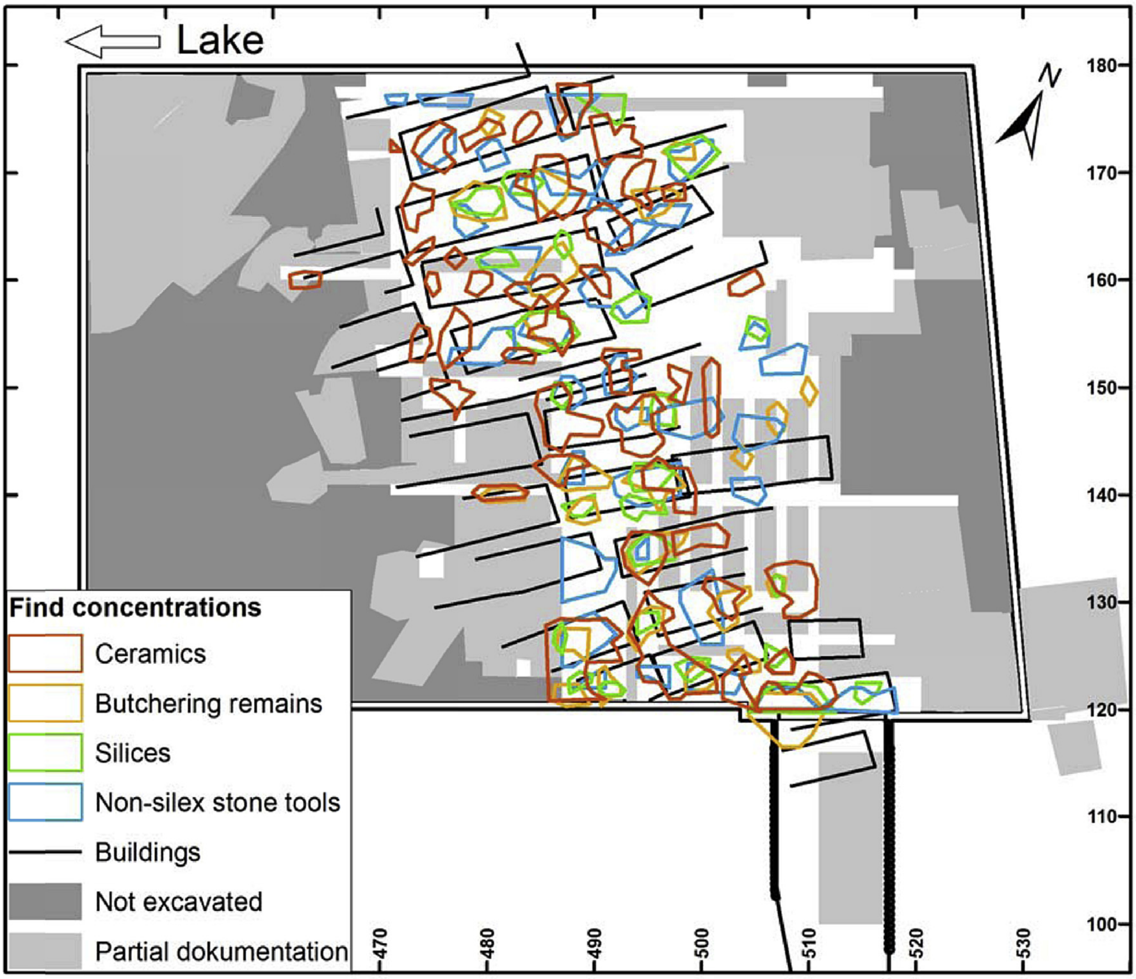

Fig. 11. Distribution of find densities of different materials in Layer 13 in relation to dendroarchaeologically defined buildings.

taxonomic resolution (data presented in Heiri et al., 2017). Chironomid groups that dominated in the lake marl were more indicative of unpolluted water and high oxygen levels. In contrast, those groups from the anthropogenic layers were more characteristic for nutrient-rich eutrophic environments with episodic low oxygen concentrations and they were found on all levels of the cultural layer that was up to 35 cm thick. The assemblages consisted almost exclusively of groups that do not tolerate desiccation and do not inhabit semi-terrestrial environments. Some of the chironomids dominating the cultural layer can burrow a few millimetres and up to few centimetres into the sediment (Heiri et al., 2017). Other regularly found groups in the cultural layer do not burrow at all. The cladoceran assemblages also showed a change to species characteristic to nutrient-rich conditions in cultural layers and to clear water conditions in the lake marl in between, although assemblage changes were less pronounced than for the chironomids (data presented in Heiri et al., 2017). Next to the compositional changes, both chironomid and cladocera concentrations (expressed in remains or head capsules cm^{-3}) tend to decrease in the anthropogenic layers and start to increase again above the cultural layers (Fig. 10), although fossil remains of both groups were common in all examined samples.

High (subannual) resolution pollen analyses revealed no levels of higher degradation in the monoliths (Gobet et al., 2017, 17).

As mentioned, Layer 14 gave generally the same results as layer 13. However, insects and small zoological remains both showed a noteworthy higher level of mechanical destruction, while botanic remains were mostly very well preserved, so that indicators of corrosive and mechanic degradation are not in agreement for this layer.

Layers 12, 15, 16 and 17 could not be as comprehensively studied due to more restricted or even missing organic preservation. However, there are notable similarities of the available results for these layers with those for Layers 13 and 14. The internal structures of the loam patches was the same as in Layers 13 and 14 with dispersed burnt fragments. Furthermore, chironomid and cladoceran assemblages give a similar picture for these cultural layers as for Layers 13 and 14 (Heiri et al., 2017, Fig. 10). Cladoceran assemblages from layers 15, 16, and 17 indicate a water quality somewhere in between that of eutrophic conditions in layers 13/14 and the more oligotrophic conditions represented by the lake marl in between (Heiri et al., 2017).

4.2. Results on find displacement and material loss in layer 13

Archaeological finds such as animal bones, silices and ceramics showed no traces of sorting based on specific weight or size. Instead, their distribution clearly followed a distinct pattern with elevated concentrations near the centres of the buildings (Fig. 11). The surfaces of the animal bones bore hardly traces of erosion such as rounding of edges. The few examples of rounded edges occur mostly in the landward half of the settlement (Schibler and Schäfer, 2017, 123). Similarly, the light *Linum* capsule fragments and remains of water plants such as *Chara* oogonia show higher values in the landward part of the site (Fig. 12).

Lateral movement and some transport of plant detritus and loam prior to sediment consolidation appears to be documented by the discovery of a pot that was deposited lying on its side. Its cavity was filled with detritus and a mineral band reflecting almost exactly the

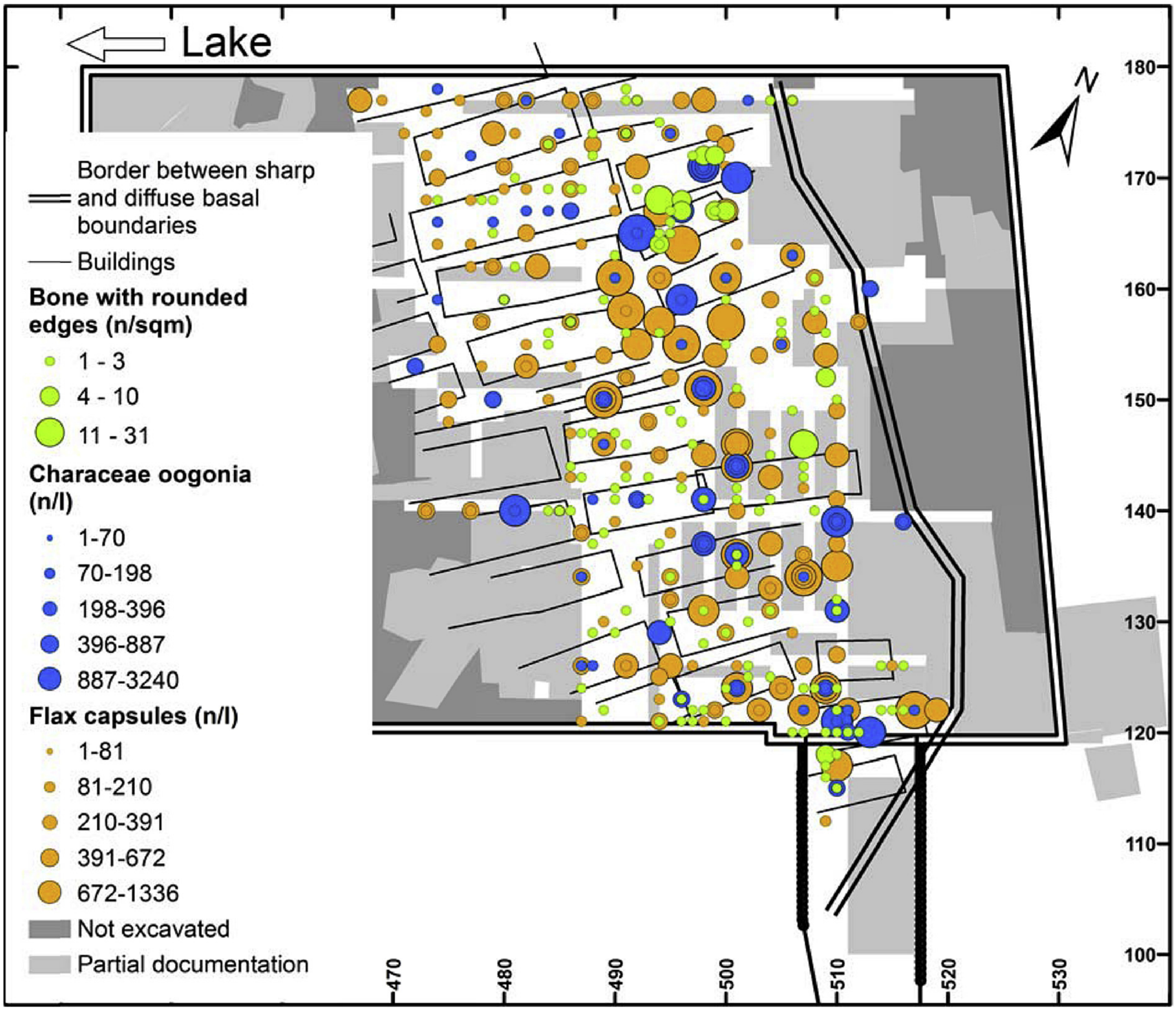

Fig. 12. Distribution of bones with traces of erosion, *Linum* capsules and Characeae oogonia.

stratigraphy in the surrounding sediments (Fig. 13). The material must have been transported into the vessel, when it was already lying in the position it was excavated in.

Similarly, subannual pollen counts gave no indication that the annual or even seasonal pollen deposition signal was preserved in the cultural layers, also pointing toward some lateral movement or bioturbation of the material (Gobet et al., 2017, 17).

Layer thickness differed considerably within the site (Fig. 14). We therefore calculated the relations between the local thickness of layer 13 and the amount of local finds of different materials (Bleicher, 2017). Ceramics, stone tools and silex showed a reduction by about 2.4% of finds per cm of reduced layer thickness, while bone was reduced by 3.5%, which is directly proportionate to the reduction of layer thickness itself (Table 1). Therefore, where the deposit was thinner, it was moderately enriched in heavier stone objects compared to bone. As we pointed out above, lightweight botanical remains were depleted in higher stratigraphical position. However, we observed no major and systematic differences between the find densities of botanical remains in the lower parts of layer 13 where it was thick and those areas where layer 13 was thin (Table 2).

For most ceramics found at Parkhaus Opéra the original vessels could not be reconstructed by matching sherds due to the sheer number and the crumbly state of the ceramics. However, for individual finds we observed that the sherds of the same pot were distributed over a number of square meters (Weber, 2016, Fig. 75).

5. Discussion

5.1. Discussion of the depositional environment

The geotechnically reconstructed palaeotopography indicates that for buildings to have been constructed on dry land the water table would have needed to be so low, that Lake Zurich would have effectively had no outflow (Schindler, 1981, 76). Furthermore, older organic deposits on the shore of Lake Zurich would have been above the water table for decades, which would have caused their degradation. However, at the neighbouring site of Zurich-Mozartstrasse (50 m from Parkaus Opéra, see Fig. 1), older deposits from the early fourth millennium BC were in excellent waterlogged condition in the 1980s at over 403.5 m a.s.l. (Ebersbach et al., 2015, 41). This is about 2 m above the level that one would have to assume for a dry land settlement in Parkhaus Opéra.

The spatial distribution of the structure of the lower margin of cultural layers agrees with this evidence. Settling on dry ground implies trampling by humans and livestock as well as bioturbation by burrowing animals. However, possible indications of such processes were only found in the landward part of our study site (Fig. 8).

The widespread occurrence and high abundances of remains of aquatic plants, insects and strictly aquatic molluscs clearly demonstrate an influence of the lake in the formation processes of the cultural layers, which speaks for deposition underwater, if synsedimentary deposition

Fig. 13. Horizontal pot filled with sediment with the same stratigraphy as the surrounding sediment layers. The arrow points at a band of micrite within the organic detritus that was also found outside the pot.

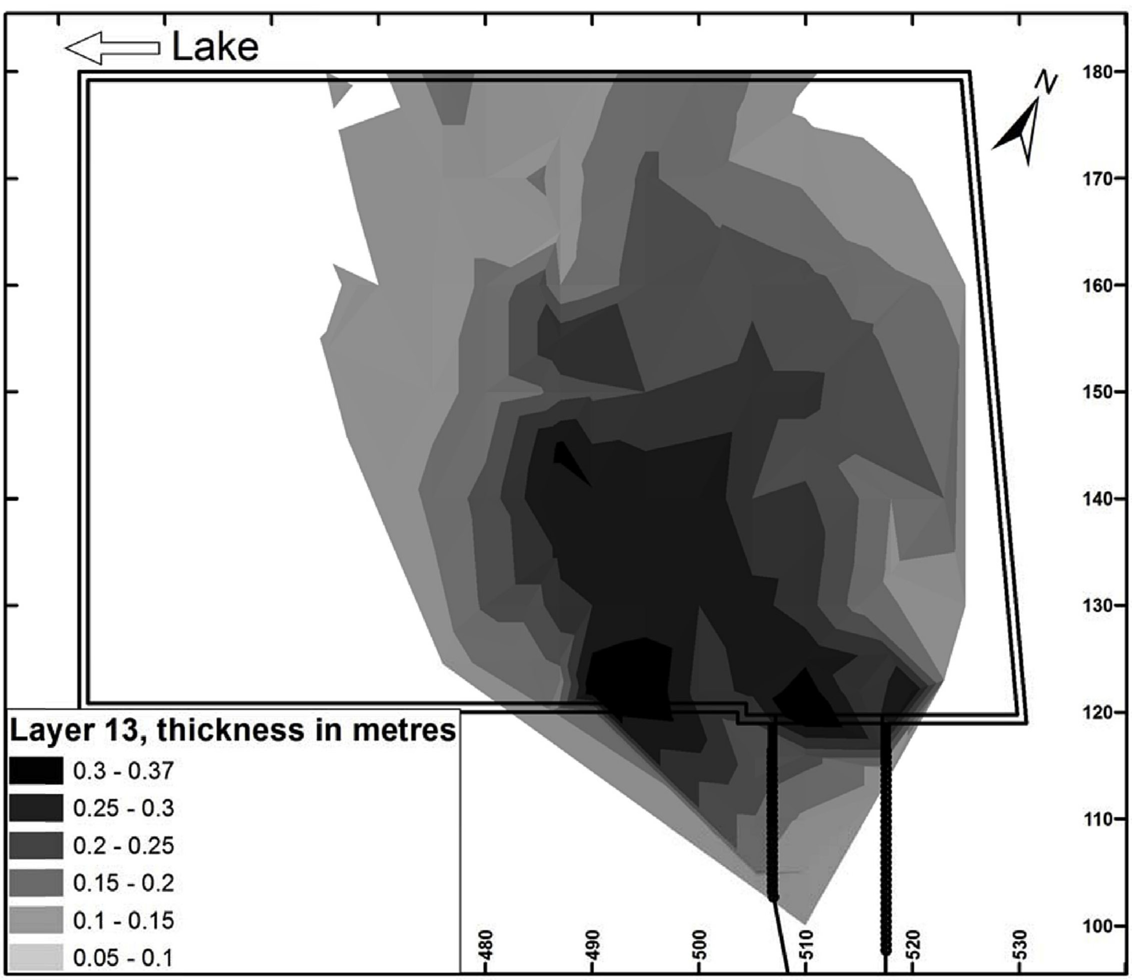

Fig. 14. Thickness of layer 13.

Table 2
Comparison of botanical find densities in lower stratigraphic units of thick layers with samples from thinner layers.

Layer13, A-Samples, Find density	Mean all Samples (n = 256)	Mean lower parts (n = 86)	Mean thin parts (n = 52)
Cerealia, Testa, uncharred	5.8	7.1	8.4
Linum usitatissimum, larger parts of uncharred capsules	40.5	45.6	43.8
Layer13, B-Samples (only 0.35 mm fraction), Find density	Mean all Samples (n = 122)	Mean lower parts (n = 37)	Mean thin parts (n = 15)
Hordeum vulgare (multi-rowed barley), rachis fragment, uncharred	101.4	102.7	144.5
Triticum dicoccon, glume base, uncharred	729.1	1123.9	933.1
Triticum durum/turgidum, rachis fragment, uncharred	270.6	483.8	227.0
Linum usitatissimum, larger parts of uncharred capsules	106.4	128.6	109.4
Linum usitatissimum, small parts of uncharred capsules	1260.6	1383.2	1790.2
Linum usitatissimum, seeds, uncharred	1105.2	1322.4	1451.3
Papaver somniferum, seeds, uncharred	5739.7	6700.5	8598.4

of these remains is assumed. This has been subject to heated debate for decades (Vogt, 1955; Thew 2004, 87/88; Bleicher, 2015). Theoretically, it is conceivable that some aquatic remains may be incorporated into terrestrially formed cultural layers after deposition as a result of flooding or post deposition contamination. However, for Zurich Parkhaus Opéra this scenario is not realistic since they are also present in organic bands between loam layers, where they were protected from later water influence. Furthermore, aquatic molluscs may have been transported to the study site due to later flooding, but the absence of terrestrial species cannot be explained by this mechanism.

Similarly, the chironomid and cladoceran remains indicate deposition under water. Since several of the observed taxa do not burrow significantly into the sediments (e.g. some Orthocladiinae and Tanytarsini groups, all observed cladoceran taxa; Heiri et al., 2017) they have not invaded the cultural layers after deposition. Furthermore, the taxa in the cultural layers are typical for eutrophic low-oxygen conditions, whereas the intermittent layers of lake marl contain taxa with different ecological requirements that are usually found in well-oxygenated, clear water conditions (Heiri et al., 2017). However, reworking of sediments and post-deposition contamination of the cultural layers would have led to similar assemblage compositions in cultural layers and encompassing micrite layers.

At some Neolithic settlement sites in Switzerland, only low concentrations of water plants in cultural layers have been documented, although other analysed indicators pointed towards an aquatic environment (Brombacher and Hadorn, 2004, 62; Hosch and Jacomet, 2004, 150; Jacomet, 1985, 60). Without speculating here what the correct interpretation in these sites might be, since this would need individual in-depth analyses, we would like to state that there need not be a contradiction in such data. Since the contents of cultural layers are typically evaluated per volume of sediment, high accumulation rates of anthropogenic material may dilute aquatic remains and lead to low observed concentrations of sediment components of aquatic origin. The representation of the aquatic indicators will therefore (among other factors such as the local topography) vary as a consequence of anthropogenic deposition rate. It can even vary over time during the same settling event. This might explain some variability in their densities in Parkhaus Opéra as well. Effects of changing deposition rate might be an issue in many sites and it stresses the importance of well constrained age-depth models. However, it is clear that in other situations changes in the abundance of aquatic plant remains may also reflect past changes in water level (Steiner et al., 2018).

In summary, our results clearly imply subaquatic deposition in shallow water with subsequent oxygen depletion during the settlement's occupation. Since most of the settlement area showed no signs of trampling and burrowing and since there were no signs of intermediate drying, an amphibic scenario, with temporarily dry surfaces at the location of the buildings is only possible for the most landward part of the settlement, where a disturbed basal transition of the cultural layer was documented (Fig. 5). Earlier empirical studies carried out at similar shoreline environments at Lake Constance (Switzerland) have shown that soil formation processes (visible as a zone of downward transport of organic substances by worm and water activity) occurred at ≥ 25 cm above the mean water table, i.e. well within the area of seasonal flooding (Ostendorp, 1992, 17).

The high nutrient and organic matter input during occupation of the settlement caused both oxygen depletion and shifts towards assemblages more typical for eutrophic environments, as apparent for chironomids, cladocerans as well as botanical and insect assemblages analysed at Zurich-Parkhaus Opéra (Heiri et al., 2017, 49; Antolín et al., 2017a, 82; Schäfer, 2017, 162). Also fish and mollusc remains provide evidence of local eutrophication (Hüster-Plogmann and Häberle, 2017, 140). The associated oxygen depletion was so severe, that some deposited leaf fragments remained green for over 5000 years, as apparent during excavation of the site.

The intermixture of remains in good and poor preservation states can be explained by taking predepositional histories of objects into account, for example if some objects were already in partially decomposed or damaged condition (e.g. due to ingestion and intestinal passage) when they entered the cultural layers. Nevertheless, it is clear that in such situations the best-preserved objects characterise the depositional environment, since these least degraded structures are indicative of the degree of oxygen availability and level of degradation experienced by all remains, fresh and partially decomposed, during the final deposition and burial in the sediments.

As mentioned above, we cannot exclude short-term drying of the accumulated sediments in the eastern, higher parts of the excavated area, although such events, if they occurred, will not have been frequent or of long duration. The distribution of floating and easily transportable plant remains such as the *Linum* capsules and of rounded bone remains indicate a zone of accumulation that can be interpreted as traces of a drift line (Fig. 9). In this area remains of beetles that live in reed were also discovered (Schäfer, 2017, 162) and micromorphological analyses revealed indicators of very shallow water in the lake marl directly below the cultural layer (Pümpin et al., 2015, 157).

It remains to be explained, why Layers 12 and 15 to 17 show very poor organic preservation compared with Layers 13 and 14. Organic deposits might be eroded after their deposition or may never have formed if nutrient input and algal production never pushed the biological oxygen demand during the respective settlement phases over the threshold to induce anoxic conditions (Bleicher and Schubert, 2015). The chironomid and cladoceran assemblages still indicate that during occupation some eutrophication and oxygen reduction took place, albeit not as pronounced as for Layers 13 and 14 (Fig. 10 and Heiri et al., 2017). Since aquatic groups dominated the invertebrate assemblages and the assemblage composition was similar as observed for Layers 13 and 14 it follows that the related settlements were also situated in the shallow water. However, the importance of erosion and degradation is as yet difficult to estimate and the taphonomy of these and numerous similar layers at other sites needs further study.

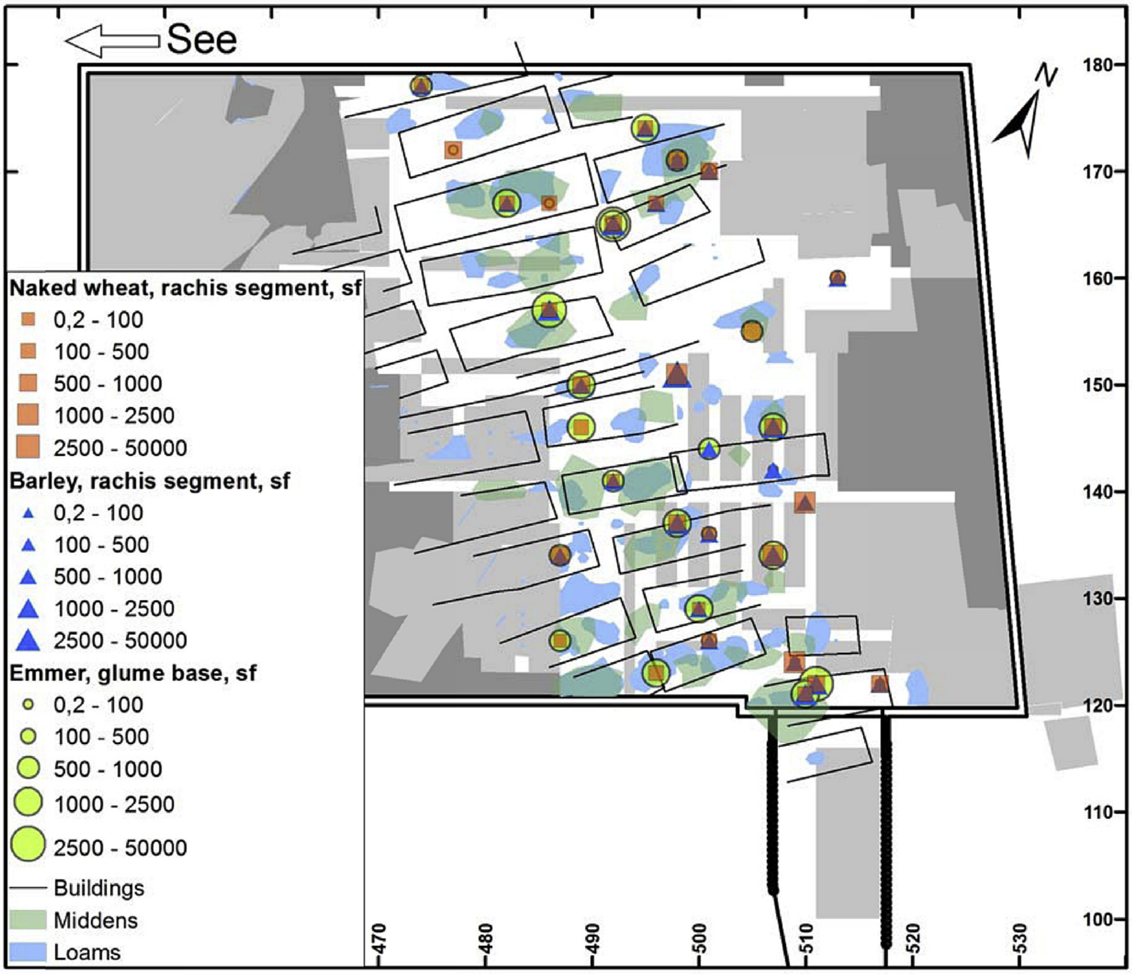

Fig. 15. Example of lightweight botanical remains in the lower part of Layer 13 with high concentration values in or close to the middens (Antolín et al., 2017a).

5.2. Discussion of find displacement and material loss

As discussed above, the available evidence implies that the houses at the site Zurich-Parkhaus Opéra were situated in shallow water. It therefore remains to be discussed, how the material was deposited, how much of what was once deposited has been preserved and whether water currents have led to find displacement and biased find distributions.

Based on our results, the observed loam patches cannot be deposited *in situ* in a strict sense, which agrees with the regular presence of baked fragments in random positions. These fragments of former surfaces and the amount of clay per loam structure (not enough to have served as plaster) indicate that the loam patches are most likely the remains of hearths that were episodically repaired. The disposal of old hearth plates took place in the same spot under the houses where household waste was dumped. This is apparent because the find concentrations with mineral deposits, such as ashes, are associated with the loams and both are located close to the centres of the buildings. Together they can be interpreted as middens. Only rarely are middens between two houses. The organic bands between loam layers obviously represent deposition between two events of hearth restoration. Available evidence thus suggests that disposal most probably happened through an opening in the floor.

The observation that these middens were still in place during excavation shows that the overall pattern of artifact distributions reflects the prehistoric customs of disposal and has not been relevantly biased by intense reworking or erosion. The previously mentioned pot filled with cultural layer and the absence of seasonal signals in the pollen profiles does, however, indicate some limited lateral movement of sediments and deposited material. Similarly, matching sherds from the same pot scattered over a few square meters, a finding previously mentioned in section 4.2, support this interpretation. However, lateral transport was obviously not enough to eliminate the distribution patterns apparent for find densities of both heavy finds such as stones and bones and of lighter ones such as different botanic remains (Figs. 11 and 15). Only few find categories, such as capsules of *Papaver* and *Linum*, were obviously and regularly subject to transport – maybe even floating on the water surface. In contrast, other botanical remains, such as glume wheat chaff, that can also be expected to float, were concentrated in the middens. This is an indication that human behaviour influenced the further path of different materials, e.g. by threshing outside or dehusking inside buildings and thus by different modes of disposal.

Some observed distribution patterns initially appear surprising. For example, some aquatic plant remains are more frequent towards the landward side of the site than in deeper water (Fig. 12). This might be explained by gentle wave action, for deposition occurs on locations where the current speed that is necessary for suspension of an object is no longer exceeded (Wright et al., 1999). This situation is typical for shores, where drift lines form, or for reed belts (Jacomet, 1985). The slightly higher frequency of traces of mechanical abrasion (Fig. 9) on plant remains in deeper water may be due to currents that occur when the backflow of waves suspends plant materials and deposits them further away from the shore.

Diminishing find densities of plant and insect remains as well as higher values in erosion indicators in the upper parts of Layer 13 are likely related to these samples originating from the upper sections of middens. The higher a midden becomes in shallow water, the closer it reaches to the water surface, where the influence of waves and currents are stronger. Taphonomic processes during midden formation therefore vary with height. Furthermore, when anthropogenic deposition suddenly stops, the cultural layer's surface will be exposed to oxic degradation and mechanical erosion until it is sufficiently covered by micrite. Therefore, a rise in indicators of erosion at the top of the layers might be a consequence of diminishing deposition rate and need not necessarily indicate a change in lake level or water currents, although this cannot be excluded.

As density of buildings and duration of occupation were roughly uniform across the entire site, it is reasonable to assume that the amount of finds, refuse and more generally speaking the overall amount of anthropogenic deposition should show a similarly uniform distribution. In contrast, our analyses of find amounts in relation to layer thickness clearly showed that in the north of the site, where Layer 13 was thinner, considerably fewer finds from this layer were recovered. The remnant cultural layer in the north was moderately enriched in heavier materials like stone and silex compared to the less-eroded layer in the south. However, if one compares only the lower part of the thicker, uneroded cultural layer in the southern part of Layer 13 with the remaining material in the thinner, northern area, then the find amounts do not differ (Tables 1 and 2). Since it appears that taphonomic processes vary with the vertical position within a cultural layer, it seems that comparisons between samples should concentrate on the lower part of the deposit, where the formation processes are similar. If this is done, then comparisons across the whole excavated area are probably more valid, because they are based on finds from taphonomically comparable contexts.

We interpret the material loss of Layer 13 to be related to rare erosional events, or even one single large event, instead of continuous erosion (Bleicher, 2017). Such an event could have eroded the upper half of the cultural layer, including the majority of stone objects, so that the observed enrichment in heavier materials is relatively moderate. Continuous material loss, in contrast, should have caused much stronger differences between the find densities of different materials according to their erodibility. It appears, that the find amounts per stratigraphical unit and, in the case of botanical remains, the density of plant remains per litre are good indicators whether samples or areas are directly comparable.

6. Conclusion

Interdisciplinary studies of taphonomic processes affecting the waterlogged deposits of the former lakeside settlement of Zurich-Parkhaus Opéra resulted in abundant evidence that the buildings of all phases were situated in the shallow water zone. Two of the settlement phases resulted in waterlogged deposits with excellent organic preservation. The mechanism that caused this preservation was oxygen depletion mediated by heavy anthropogenic organic input and subsequent degradation and associated eutrophication. We argue that in the other settlement phases the balance between oxygen demand due to degradational processes and oxygen supply did not reach the threshold to induce complete oxygen depletion and therefore did not promote similarly excellent organic preservation. Possible reasons are changes in deposition behaviour of the settlement occupants or changes in water currents as well as settlement duration and intensity.

Available evidence indicates that the deposited material experienced limited lateral transport, with the exception of few types of very light remains (e.g. flax capsules) which were distributed more widely, probably floating on the water. The overall distribution patterns appear to faithfully mirror human customs of disposal on rubbish heaps, that were mostly under and sometimes between the buildings.

There are strong indications that the taphonomic processes within the anthropogenic deposits varied and especially so with stratigraphic position within the layers. The higher in the stratigraphy (even within a given layer) the more intense degradation, erosion, selection and enrichment are reconstructed, so that samples from the top of middens are difficult to compare with samples from the bottom. Comparisons between households therefore should focus on samples from the same relative position within the cultural layer with similar levels of find densities.

In the northern part of the settlement, at least the upper half of cultural layer 13 was apparently removed, probably by a single erosion event at the end of or shortly after the occupation. In this area the remnants of this layer largely correspond to the lower part of the cultural layer in the non-affected parts of the settlement. Therefore, the whole excavated area can be utilized for analyses of find distributions, if the focus is on find material from the lower part of the cultural layer.

Our results show that for archaeological sites of former lakeside settlements the remains of fully aquatic organism groups (e.g. chironomids, cladocerans, aquatic macroremains) belong to the most powerful indicators to characterise the former depositional environment, particularly in combination with in-depth evaluations of rectified profile-photographies and basic numerical analyses of find densities with respect to spatial distribution, stratigraphical position and specific weight. Only such a multi-indicator approach makes it possible to reconstruct and understand the main depositional processes active at such sites.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2018.06.010.

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